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[MIDDLE ULTRAVIOLET DAY RADIANCE OF THE ATMOSPHERE]

by

J. P. Hennes, W. B. Fowler, and L. Dunkelmann

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Goddard Space Flight Center

National Aeronautics and Space Administration,
Greenbelt, Maryland

1606771

ABSTRACT

The day radiance of the atmosphere has been measured, photoelectrically, at two middle ultraviolet wavelengths by rocket-borne photometers. Filters and collimators provided an effective field of view of 1.4×10^{-2} steradians, and bandpasses of approximately 100A at 2600A and 230A at 2200A. At a height of 146 km, nadir radiance values of about 0.5 ergs/sec cm² ster 100A were obtained at both wavelengths. There is good agreement between the radiance values measured and those which have been calculated on the basis of single Rayleigh scattering in the presence of ozone. From the radiance data an atmospheric diffuse reflectivity of about 8×10^{-4} at 2600A has been calculated. This may be contrasted with 1957 rocket observations of Mars and Jupiter which yielded albedos at 2700A of 0.24 and 0.26 respectively.

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I. INTRODUCTION

If the earth's sunlit side is viewed from space it exhibits a bright appearance in the visible portion of the spectrum. In contrast, the appearance of the sunlit earth in the ultraviolet wavelength region below about 3100A may be expected to be rather dim and relatively uniform. In the visible region the upward flux out of the atmosphere is made up of Rayleigh scattered sunlight, sunlight reflected directly from clouds or from the earth's surface, light scattered from atmospheric dust, and a relatively small amount of resonant and fluorescent scattered sunlight or day airglow. In the middle ultraviolet region from 2100 - 3000A, however, because of the totally absorbing ozone region located from approximately 10 to 40 km, the day radiance will be produced only by Rayleigh scattering of sunlight in the thin upper atmosphere above the ozone region and by fluorescent scattered sunlight or ultraviolet dayglow. The combination of a thin atmosphere and strong ozone absorption produces a correspondingly low albedo. The absence of contributions from reflections by clouds and surface features and the strong wavelength dependence of Rayleigh scattering will produce a relatively uniform appearance.

The spherical albedo of a planet is the ratio of the total flux emitted in all directions by the planet to the total flux incident on the planet from the sun. Both quantities are being measured over the same wavelength interval. The earth's visual, spherical albedo has been experimentally determined, by studies of earth light on the moon, to range from 0.29 - 0.56 depending on the season and on which side of the earth is facing the moon. The average value of these visual albedos is given as 0.39 - 0.40 (Danjon, 1954; Dzhasybekova, Kazachevskii, and Kharitonov, 1960). The major part of the earth's visual albedo comes from contributions by reflection from clouds. If atmospheric scattering is considered separately, assuming no clouds, calculations (Kano, 1958) show the spectral albedos due

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to Rayleigh scattering to be: infrared region - .0075; visible region - 0.033; and near ultraviolet region - 0.23. The weighted sum of these various spectral albedos for a Rayleigh atmosphere is given as 0.066 by Kane (1953) for the entire spectral region $\lambda > 2900 \text{ \AA}$, and has been independently calculated by Coulson (1959) to be 0.069. The contribution in these spectral regions from airglow is negligible except over narrow wavelength intervals near the more pronounced dayglow emission lines. The uses and difficulties of dayglow measurements have been summarized recently by Chamberlain (1963).

The calculations which have been made for scattered solar radiation in the near ultraviolet have included multiple scatterings, ozone distributions, and upward and downward fluxes (Sekera and Dave, 1961a; and Larsen, 1959).

In the middle ultraviolet region calculations have assumed single Rayleigh scattering with ozone absorption (Ban, 1962; Hubbard, 1963; Green, 1964; and Krashy and McKee, 1964). Multiple scattering or fluorescence has not been included. The middle ultraviolet day radiance must originate in scattering above the ozone region. This insures a relatively small flux since even the high altitude ozone distribution is strongly absorbing in this spectral region. Dalgarno (1962, 1963) and Chamberlain and Sobouti (1962) have derived equations to show the effect of non-Rayleigh resonant and fluorescent scattering near atomic and molecular resonance lines, and point out that this effect could be significant in the ultraviolet where small Rayleigh scattered fluxes are expected.

II. THE EXPERIMENT

At 1155 EST (1655 UT) on 8 August 1962 two middle ultraviolet photometers were included in an Aerobee rocket (NASA 4.60) launched from Wallops Island, Virginia. Measurements of the ultraviolet day radiance were taken continuously as the rocket climbed to a peak altitude of 150 km. Each photometer consisted of a mechanical collimator, a filter, and a photomultiplier sensitive only to ultraviolet radiation. The

collimator produced an effective field of 1.4×10^{-2} ster (about a 7 degree square field). The filters were of the type described by Childs (1961). The phototubes were type EMR 541F-05 photomultipliers with sapphire windows and cesium-tellurium cathodes (Dunkelman, Fowler, and Hennes, 1962).

The relative spectral response of these photometers is given in Figure 1 on an equal energy basis (amps/watt). Also included in Figure 1 is the solar spectrum, averaged over 10A intervals, taken from data reported by Wilson, et al., (1954) and Malitson, et al., (1960). The effective wavelengths of the photometers were at 2217A and 2610A with effective bandwidths of 230A and 100A respectively. The contribution from the long wavelength region beyond 2800A has been examined and found to be much less than the magnitudes of the radiance measurements made.

During the flight the rocket pitched through a wide range of zenith angles. Its motion, however, was confined by an attitude control system to a single plane having an azimuth of 175° passing through the zenith and the sun. The sun was at a zenith angle of 22° . The photometers, which were pointed out the side of the rocket approximately in the pitch plane and at an angle of 122° with the rocket axis, swept from the nadir up to a zenith angle of about 80° in both the north and south sky at various times.

III. RESULTS

The data are shown in Figure 2 which give (curve a) the zenith angle of the photometers as a function of both flight time and altitude. The aspect data was obtained from solar sensing aspect cells, magnetometers, and the attitude control system error signals and pitch-rate signals. During the flight the rocket's attitude control system malfunctioned to the extent that, although controlled in two axis, the vehicle pitched through much larger angles than those for which the aspect instruments had been designed. Pitch rate signals were integrated to find approximate zenith angles outside of the region of

aspect sensor operation. These calculations could be checked by fitting with the aspect signals as the rocket periodically moved back thru the sensor region. The photometer data, reduced from the original telemetry record at one second intervals, are shown in curves (b) and (c). Relative intensity is plotted, with the data normalized to unity for nadir (180°) values. The scatter in the relative intensity values is produced by photometer noise introduced because the signal level was near the bottom of a three-decade logarithmic scale. The photometer sensitivity in this exploratory measurement had been set low to avoid the possibility of saturation due to either unexpectedly large reflectivities or unusually intense dayglow or auroral emissions. Lines have been added to clarify the peaks beyond 260 seconds.

In Figure 3 the data are replotted as a function of zenith angle. Data are shown only for 10 degree intervals of zenith angle. Part of the spread in the points is due to photometer noise, part is due to combining data taken at the same zenith angles but from different altitudes.

The values of day radiance measured during this flight are notable for the lack of features seen over a large range of zenith angles. Even the horizon brightening is only a factor of two times the nadir radiance. The photometer field of 1.4×10^{-2} steradians would, of course, diminish the effect of any increased radiance that extended over only a relatively narrow field.

The peaks at about 272 seconds in Figure 2 represent direct sunlight reflected off the photometer entrance. The photometer was pointed up in the southern sky at that point at a zenith angle of about 70 degrees. The magnitude of the reflected solar signal under those conditions was determined by laboratory measurements to be about 10^{-5} that of direct sunlight. Note that this scattered light signal is still larger than the earth radiance signal. The problem of making measurements in the presence of direct sunlight is emphasized by this result.

The magnitude of the radiances detected by the photometers is expressed in Table I. The nominal effective wavelength and the effective bandwidth are given. The third column gives the earth's radiance, at the nadir, with the sun at 22° zenith angle, assuming a uniform and equal distribution across the wavelength region described by the effective bandwidth. The equivalent photon emission rate in kilo-rayleighs per 100A is also given. The day radiance values determined by these measurements have uncertainties of about 10 - 15% arising from noise in the photometer signal and uncertainties in ultraviolet radiometric standards.

The last column gives the diffuse spectral reflectivity of the earth's sunlit atmosphere averaged over each of the wavelength intervals. This number is arrived at by assuming the scattered sunlight has the same spectral distribution as the incident sunlight throughout each bandwidth (see Figure 1). The values of solar irradiance are taken from the sources cited. The uncertainties in the calculated reflectivities are greater than those for our observed radiance values by the amount of uncertainty in published absolute spectral solar intensities. If we make the further assumption that the entire earth is a diffuse Lambert reflector, then the diffuse reflectivity of about 8×10^{-4} at 2600A becomes the earth's spherical albedo. This number can be contrasted with the earth's total observable spherical albedo of 0.39 - 0.40, and with the calculated Rayleigh scattered albedo contribution in the near ultraviolet of 0.23 as given in the introduction.

Of interest also is a comparison of the earth's low middle ultraviolet effective albedo with measurements of the relatively high effective albedos of Mars and Jupiter made in 1957 with a photometer of about 300A bandwidth centered at 2700A (Boggess and Dunkelman, 1959). They obtained values of about 0.24 for Mars and 0.26 for Jupiter.

One other known experimental observation has been made of the middle ultraviolet day radiance. Friedman, Rawcliffe, and Meloy (1963) have reported a satellite borne photometer measurement of the day radiance with a spectral pass band of 140Å centered at 2550Å. Their result, with the sun at a zenith angle of 49° and the detector pointed at the nadir with a field of 1.2×10^{-4} steradian, showed an atmospheric radiance of 2.0 ± 0.3 ergs/sec cm^2 ster 100Å.

Table II gives the various measured and calculated middle ultraviolet day radiance values. The calculated values tend to support our results rather well. It should be borne in mind that the data were all taken or calculated using different parameters of altitude, solar zenith angle, ozone distribution, season, etc. so that the results cannot be compared too directly. The relatively large factor of four between the experimental results of Friedman, Rawcliffe and Meloy and ourselves is possibly explained by either a large change in the high altitude ozone distribution between the time of the two measurements or the difficulties in maintaining calibration during the preparations for and launching of a satellite. The similarity of the various calculations and our measurements indicate that the simple approach to ultraviolet atmospheric radiance calculations, involving use of ozone distributions and single scattering with plane atmospheres (Ban, 1962; Hubbard, 1963; and Green, 1964) or spherical atmospheres (Hrasky and McKee, 1964) is adequate for broadband measurements. If higher spectral resolution were to be considered the agreement might be strongly affected by resonant or fluorescent scattering.

The calculated results depend very strongly on ozone distribution, especially in the region around the peak of the ozone absorption curve at 2600Å where the very high altitude ozone has a dominant role. The ozone distribution at higher altitudes is relatively unknown, however, so that appreciable

uncertainties may be introduced into the calculated values. At the shorter wavelength region around 2200A and at longer wavelengths beyond 2800A the ozone is much less absorbing and incident solar radiation will penetrate more deeply into the atmosphere, thus permitting more scattering and producing higher albedos. By use of satellite-borne photometers with narrow spectral bandpasses, well removed from strong dayglow emission lines, and situated at various middle ultraviolet wavelengths from 2100 and 3000A, a profile of high altitude ozone distribution should be obtainable. Such an idea was proposed in 1957 by Singer and Wentworth (1957), who considered only wavelengths at 2800 and 3000A. Twomey (1961) carried out further calculations in this same wavelength region. The calculations in the near ultraviolet above 3000A have been considered in detail by Sekera and Dave (1961b). The altitudes above 50 km would require, however, use of wavelengths below 2800A where analysis should be much easier. The seasonal and latitudinal variations in upper atmosphere ozone, so important to atmospheric heating processes, would thus be available.

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TABLE I. Ultraviolet Day Radiance Measurements of the North
 Taken 8 August 1962, at 146 km, with Photometers
 Pointed at the Nadir; Solar Zenith Angle 22° .

Nominal Wavelength (Å)	Effective Bandwidth (Å)	Radiance (ergs/sec cm ² ster 100Å)	Emission Rate (kilorayleigh/100Å)	Diffuse Reflectivity
2600	100	0.5	8×10^2	8×10^{-4}
2200	230	0.5	7×10^2	3×10^{-3}

Table II. Comparison of Measured and Calculated Nadir Ultraviolet Day Radiance Values. Radiance in ergs/sec cm² ster 100A.

Source	2600A Region			2200A Region			Solar Zenith Angle
	Average Radiance Over Interval (a)	Wavelengths		Average Radiance Over Interval (a)	Wavelengths		
		(A)	(A)		(A)	(A)	
This work (b)	0.5	2560-2660		0.5	2100-2330		22°
Friedman, et al. (1963) (b)	2.0	2480-2620		---	---		49°
Ban (1962) (c)	0.5	2550-2650		---	---		0°
Hubbard (1963) (c)	0.4 (d)	2550-2650		---	---		0°
Green (1964) (c)	0.5 (e)	2550-2650		0.7	2100-2330		0°
Hrasky & McKee (c) (1964)	0.4	2550-2700		0.5	2000-2400		22°

(a) Values estimated or rounded off from data published by the referenced authors.

(b) Measured values.

(c) Calculated values.

(d) A range of 0.05 - 0.8 is estimated depending on the ozone distribution chosen. The radiance listed is taken from Figure 14 representing a "standard" ozone curve.

(e) A range of 0.15 - 0.6 is estimated depending on the ozone distribution chosen. The radiance listed is taken from Figure 6 representing an analytical fit to the same "standard" ozone curve as used by Hubbard.

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Figure Captions

- Figure 1. Photometer response curves. Relative response of both photometers is shown on an equal energy basis. The solar spectrum, averaged over 10A intervals, is also shown. (Wilson, et al., 1954; Malitson, et al., 1960). The 2200A photometer response is provided by a combination of an interference filter and 4 mm $\text{NiSO}_4(\text{H}_2\text{O})_6$ crystal. The 2600A photometer combines an interference filter, Corning 7-54, 4 mm $\text{NiSO}_4(\text{H}_2\text{O})_6$, Cation-X, and 2 mm Pb doped KCl:KBr crystal (Childs, 1961).
- Figure 2. Rocket flight data. Curve (a) is the zenith angle of the photometer direction as a function of time. Curves (b) and (c) are a sampling of the reduced telemetry data plotted in terms of the relative intensity received by the photometer. The points show scatter produced by photometer noise and a small amount of structure as a function of zenith angle. The peaks after 200 seconds correspond to the horizon limb brightening. The large peak at 273 seconds, which is extraneous, is produced by sunlight reflected off the photometer entrance with the photometers pointed above the horizon in the south. Without this sunlight effect the record would appear as it does at 310 - 320 seconds with the photometers pointed above the horizon in the north.
- Figure 3. Ultraviolet day radiance as a function of zenith angle. The data in Figure 2 are replotted here as a sampling of telemetry data taken at 10 degree intervals. The crosses indicate data taken at altitudes less than 120 km. Circles indicate data taken at altitudes above 120 km. Solid circles are single points, open circles represent several data points (2-5) occupying the same position. The limb brightening is evident.

as is the fairly sharp drop at zenith angles less than about 90° as the photometer points up above the atmospheric horizon.





